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August 5, 2016

Dr. Robert Headrick
ONR Code: 332
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

Dear Dr. Headrick,

Attached please find the progress report for ONR Contract N00014-14-C-0230 for the period of October 20, 2015 to January 19, 2016.

James C. Preisig
President, JPAnalytics LLC

CC: DCMA Boston
DTIC
Director, NRL

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Progress Report #7

Coupled Research in Ocean Acoustics and Signal Processing for the Next Generation of Underwater Acoustic Communication Systems

Principal Investigator's Name:	Dr. James Preisig
Period Covered By Report:	10/20/2015 to 1/19/2016
Report Date:	8/5/2016
Contract Number:	N00014-14-C-0230
Firm Name and Address:	JPAnalytics LLC 638 Brick Kiln Road Falmouth, MA 02540 jpreisig@jpanalytics.com (508) 566-0236
Program Officer:	Dr. Robert Headrick ONR Code: 322 Office of Naval Research 875 North Randolph St. Arlington, VA 22203-1995 Robert.Headrick@navy.mil
Security Classification:	Unclassified
Distribution Statement:	Approved for public release. Distribution is unlimited.
Total Contract Amount:	$595,731
Costs Incurred This Period:	$43,811.34
Costs Incurred To Date:	$281,166.89
Estimated Costs To Complete:	$314,564.11

1. **Description:** Technical work this period has spanned three areas. The first of these is VHF Acoustics. During this time period, the Principle Investigator continued the analysis of data collected during the VHF acoustics test conducted in a wave tank at the Scripps Institution of Oceanography in October 2015. Numerous insights were gained from the analysis and are described more fully in the Results and Recommendations section of this report. The results of the analysis of the data were presented at the 170th meeting of the Acoustical Society of America in Jacksonville, FL in November 2015. Planning for a follow-on experiment at the same location (Scripps Institution of Oceanography) commenced. In parallel, the Principle Investigator continued to work with vendors to develop a new field deployable system for collecting VHF acoustic data in a wide range of environments. This work falls under Research Task 2 from Section 2.2 of the Technical Approach and Justification.

   The second area of work is that of characterizing the performance of adaptive equalizers in order to evaluate different system configuration trade-offs with respect to their impact on communications performance and ease of implementation. Work in this time period shifted from extending asymptotic Random Matrix Theory to explicitly handle time-varying environments to using the standard established theory for time-invariant environments with the impact time-variability accounted for by limiting the averaging interval of the equalizer adaptation algorithms to that over when the environment can be considered time-invariant. Work continued on a simulation environment based around the PC-SWAT propagation model in order to generate data for estimating signal statistics and for comparing theoretical RMT based performance predictions and the performance of algorithms operating on the data generated by the simulator. This work falls under Research Task 1 from Section 2.2 of the Technical Approach and Justification of the contract proposal. The results of the first part of the analysis of simulation based performance predictions was presented in a special session on Underwater Acoustic Communications at the Asilomar Conference on Signals, Systems, and Computers in November, 2015.

   The third area of work involved the development of new methods of applying reduced-dimensional inference algorithms to improve the performance of or reduce the computational complexity of coherent equalizer adaptation algorithms. This is joint work with MIT/WHOI Joint Program Student, Atulya Yellepeddi and is motivated by the desire to exploit lower dimensional structures in acoustic communications data, specifically frequency domain transformations of received communications signals, to achieve the specified improve-

ments. The work this quarter focused on the development and analysis of an Expectation Maximization (EM) based technique that exploits a proposed graph structure of the data to improve performance. This work falls under Research Task 3 from Section 2.2 of the Technical Approach and Justification.

2. **Major Accomplishments this Period:** The analysis of the first successful SIO tank experiment was a major accomplishment. Insights and recommendations for modifications to subsequent experiments are listed the Results and Recommendations section.

3. **Results and Recommendations:**

   The VHF acoustic wave tank experiment created new insights into surface scattering in this regime. Due to the very short wavelength (approx. 2.7 mm at the center frequency of 550 kHz) very small waves (including capillary waves) have an effect on surface scattering. Noticeable effects on the scintillation index and scattering function (particularly Doppler spread) start at wind speeds of less than 2 meters/second. As noted in Progress Report 7, the first of these is that the surface scattered signal shows an asymmetric Scattering Function with the positive Dopplers showing both a higher scattered intensity and longer delay spread. Figure 1 in this report shows the Doppler Power Profile for both the direct (black) and first surface bounce (red) arrivals averaged over the receive array elements. The labels for each subfigure indicate the wind speed used to generate waves in the tank. The surface scattered signal shows the slight asymmetry that the qualitative viewing of the scattering function of the surface scattered signal suggested would exist.

   A striking characteristic of this data is the Doppler spreading of the direct path signal (black) that increases with increasing wind speed. With minimal wave motion penetrating to the depth of the acoustic transmitter and receiver, one would would expect no meaningful Doppler spreading of this signal. Further consideration and analysis indicate that this is likely due to the increasing vibration of the acoustic array mounting mechanism as wind speed increases. With acoustic wavelengths of approximately 0.1 inches, it is very conceivable that the vibrations of the mounts, which are fastened at a single point at the top of the wind/wave tank, will be order a wavelength or more thus imparting a significant Doppler spread on the received signal. This has been noted and Dr. Grant Deane at Scripps Institution of Oceanography, the co-PI on these experiments, undertook the design and fabrication of a new mounting mechanism to eliminate this mounting induced Doppler spreading of the signal.

While this mounting mechanism improvement will be beneficial from a scientific point of view, the sensitivity of the signal to very small mechanical vibrations of the receiving hardware raises questions regarding the modeling of received signal characteristics for actual applications such as underwater acoustic communications systems. It is likely that operational platforms, including AUVs, will be subject to some mechanical vibrations. While these vibrations are traditionally modeled as comparatively low frequency noise because the displacement of the vibrations is small compared to a wavelength, such may not be the case for VHF acoustic systems. It may be that the amplitude of displacement induced vibrations may be order a wavelength or more and thus induce a platform vibration induced Doppler spreading on the received signals that will need to be accounted for in algorithm motion compensation and performance modeling.

Figure 2 shows the Doppler spreading (solid lines) and mean Doppler offset (dashed lines) of the received signal as a function of wind speed. The red lines are for the surface bounce path signal while the black lines are for the direct path signal. The solid blue line shows the difference between the Doppler spread of the direct and surface bounce path signals and represents, to a first order, the Doppler spreading that can be attributed to the time-varying scattering from the waves on the water surface. Several features are worth noting. The first is that the mean Doppler shift of the direct arrival is minimal thus indicating that the asymmetric Doppler spreading of the surface bounce signal is not induced by the transmitter or receiver motion but by a asymmetry in the surface scattering. The second thing to notice is that the Doppler spreading attributable to the surface scattering (solid blue line) begins to saturate as wind speed increases. A future experiment, in addition to using an improved mounting mechanism, will collect data over a wider range of wind speeds to attempt to determine if this saturating is indeed happening and if so, the causal physical mechanism.

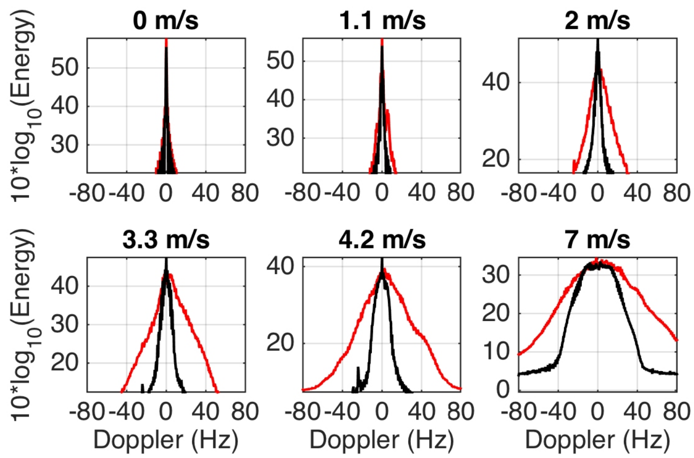

Figure 1: Doppler Power Profile for Direct and Surface Scattered Signals

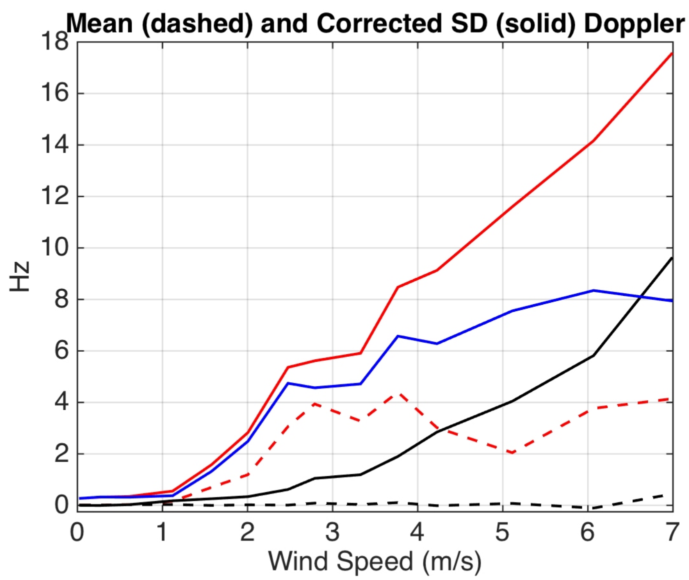

Figure 2: Doppler Spread of Direct and Surface Scattered Signals

The received signals were also analyzed for the scintillation index of the statistical fluctuations of the channel impulse response, particularly for the surface scattered channel. The statistics of the channel fading as this is called in the communications literature, is an important factor in determining the nature

of optimal signal equalization, demodulation and decoding algorithms. As a first look at the statistics, the Scintillation Index (traditional narrowband definition) was calculated as a function of arrival delay and wind speed. Figure 3 shows the received signal intensity (top subfigure) as a function of delay and windspeed. This shows a delay spreading of both the direct arrival (nominally about 30 μS delay) and the surface bounced arrival (nominally about 80 μS delay). Interestingly, the direct arrival moves later in delay as the wind speed increases. This may be due to mean offset in the location of the source or receiver (most likely receiver) related to bending of the mounting mechanism or another physical factor. A repeat of this experiment with a sturdier mounting mechanism will help resolve this question. Tracking along the peak of the peak amplitude response of the surface bounce arrival is the black of the top subfigure.

The bottom subfigure shows the same line superimposed upon the log of the scintillation index of each arrival shown in the bottom subfigure. There is a substantial area corresponding to very low energy levels shown in the top subfigure in dark blue for which the scintillation index is not relevant to this study. These areas are shown in white in the lower subfigure. The scintillation index along the black curve in the lower subfigure is plotted as a function of wind speed in Figure 4. The six curves correspond to the scintillation index measured at each of the six receive array elements used in the experiment. Note that the scintillation index rises quickly at wind speeds above 1 m/s, briefly saturates at 1.0 for all except one array element and then begins to rise again.

In comparison, Walstead and Deane conducted a similar experiment with a center frequency of 300 kHz. The measured scintillation index of the surface bounce arrival did not begin to rise significantly until the wind speed exceeded 2 m/s and then stabilized at a value of 0.5 up to the maximum observed wind speed of 7 m/s. With a stabilized array mounting mechanism and the observation of signals over a broader range of wind speed, the planned follow on experiment will provide useful data for building upon these insights and resolving questions regarding the statistical nature of both the Doppler spreading and channel amplitude fading characteristics of surface scattered signals in the VHF regime.

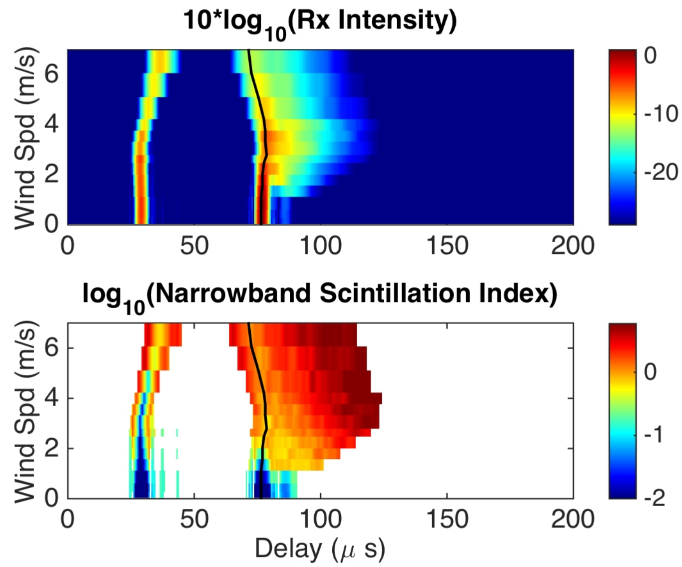

Figure 3: Received Power and Scintilation Index of Arrivals

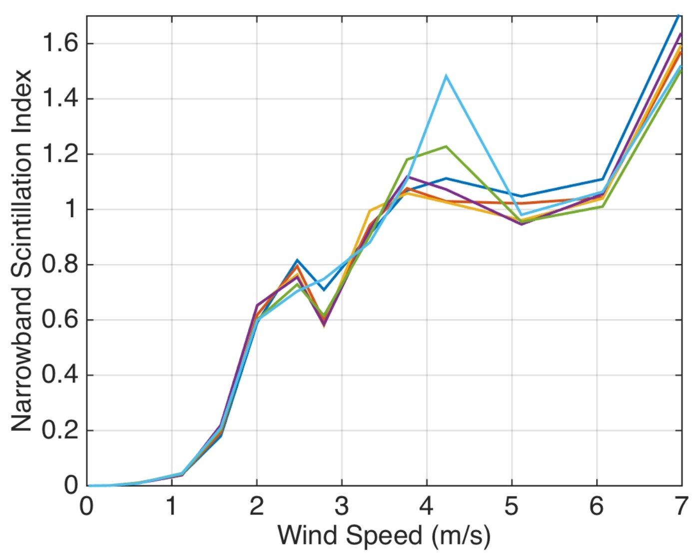

Figure 4: Narrowband Scintillation Index vs Wind Speed

4. **Publications and Presentations:** This period, the author attended and gave presentations at both the 170th Meeting of the Acoustical Society of America in Jacksonville, FL and the 49th Asilomar Conference on Signals, Systems and Computers. The papers presented included

   A. Yellepeddi, J. Preisig, "The surprising sample covariance matrix: Unexpected characteristics and understanding them", at *170th Meeting of the Acoustical Society of America*. Jacksonville, FL, Nov. 2-6, 2015. (NOTE: This paper received the award for the Best Young Presenter Paper in Signal Processing.)

   J. Preisig, G. Deane, "Coherent, very high frequency underwater acoustic communications under wind-driven seas: Experiments in an ocean simulator", at *170th Meeting of the Acoustical Society of America*. Jacksonville, FL, Nov. 2-6, 2015.

   J. Preisig, "Challenges and Analysis of Adaptive Multichannel Equalization for Large-N Arrays", at *Conference Record of 49th Asilomar Conf. on Signals, Systems and Computers*, Nov. 8 - 11, 2015, pp. 239-243.